Biologically Inspired Intelligent Robots Using Artificial Muscles

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Abstract

Humans throughout history have always sought to mimic the appearance, mobility, functionality, intelligent operation, and thinking process of biological creatures. The emergence of biologically inspired technologies, i.e. biomimetics, has made it increasingly easier to develop robots with such capabilities. Some of the technologies that have evolved include artificial muscles, artificial intelligence, and artificial vision to which significant advancements in materials science, mechanics, electronics, and computing science have contributed greatly. One of the newest fields is the artificial muscles, which is the moniker for electroactive polymers (EAP). To take advantage of these materials, efforts are made worldwide to establish a strong infrastructure ranging from analytical modeling and comprehensive understanding of their response mechanism to effective processing and characterization techniques. The field is still in its emerging state and robust materials are still not readily available however in recent years significant progress has been made and commercial products have already started to appear on the market. This paper covers the current state-of-the-art and challenges to making artificial muscles and their potential application to biomimetic robots

Introduction

In December 2002, the Japanese company called Eamex produced robot fish that swims in a water tank without batteries or a motor (see Figure 1). For power these robots use an inductive coil that is energized from the top and bottom of the fish tank. Making a floating robot fish may not have been an exciting event, but this one is the first commercial product that uses electroactive polymers (EAP) and this marks a major milestone. For their functional similarity to natural muscles EAP materials have earned the name artificial muscles.

FIGURE 1: The first EAP-based commercial product – a robot fish (Eamex, Japan).

EAP are materials that change shape and size when stimulated by an electric current or voltage. The EAP materials that have been developed so far are still exhibiting low conversion efficiency, are not robust, and there are no standard materials available commercially for consideration in practical applications. In order to be able to take these materials from the development phase to application as effective actuators, there is a need for an established infrastructure. For this purpose, efforts are made to develop comprehensive understanding of EAP materials' behavior, as well as effective processing, shaping and characterization techniques. The technology of artificial muscles is still in its emerging stages but the increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors are leading to a rapid progress.

In 1999, in an effort to promote faster advancement in this field, the author posed a challenge to the worldwide research and engineering community to develop a robotic arm that would wrestle against human opponent and win. More than ever, the launch of the first competition seems to be a matter of few years rather than decades. A graphic rendering of this challenge is illustrated in Figure 2. Reaching the level that allows for the success in wrestling against human will enable capabilities that are currently considered science fiction. It would allow applying EAP materials to affect many aspects of our life with some of the possibilities include effective implants and prosthetics, realistic biologically inspired robots and products with unmatched capabilities and dexterity. Recent advances in understanding the behavior of EAP materials and the improvement of their efficiency led to more than just the first commercial product that was mentioned above. The most recently notable milestone is the announcement of EAP scientists from SRI International that they could build a robot arm with artificial muscles that could wrestle a human and possibly win. To plan the first international arm-wrestling competition an effort is underway to raise a prize while considering holding the competition in March 2005 as part of the International Society for Optical Engineering (SPIE) Annual International EAPAD (EAP Actuators & Devices) Conference in San Diego, California [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/armsports.htm].

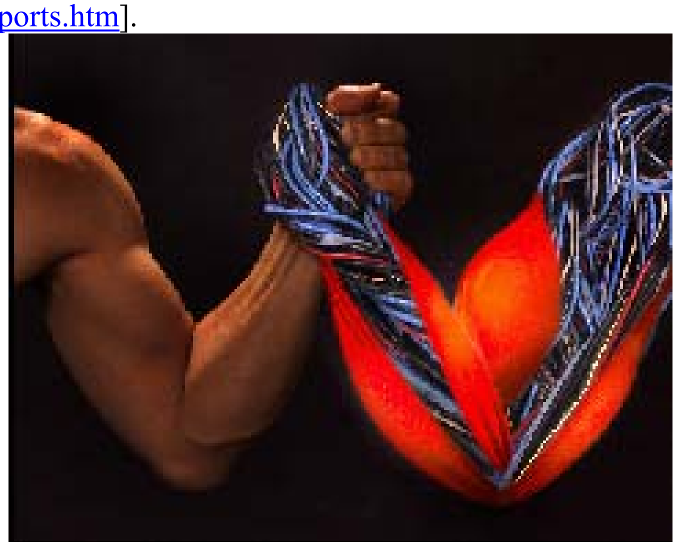

FIGURE 2: Grand challenge for the development of EAP actuated robotics.

Having actuation capability in addition to the other advantages of polymers including lightweight, inexpensive, and fracture tolerant makes these materials highly attractive. As polymers, EAP can potentially be configured into almost any conceivable shape and their properties can be tailored to suit a broad range of requirements. Since the early 1990s new EAP materials have emerged that produce significant shape and size change in response to electrical stimulation [Bar-Cohen, 2001]. Practitioners in biomimetics are particularly excited about these materials since they can be used to mimic the movements of humans and animals [Bar-Cohen and Breazeal, 2003].

The types of available Electroactive Polymer (EAP) materials

Electrical excitation is one type of the stimulators that can produce elastic deformation in polymers. Other activators include chemical, pneumatic, optical, and magnetic. Polymers that can be stimulated to change shape and size have been known for years with some that exhibit even much higher actuation strain and stress than most EAP materials. However, the convenience and the practicality of electrical stimulation, as well as the improved capabilities, led to a growing interest in EAP materials.

Generally, the EAP materials can be divided into two major categories based on their activation mechanism: electronic and ionic. Most electronic polymers (electrostrictive, electrostatic, piezoelectric, and ferroelectric) require high activation fields (>150 V/μm) close to the breakdown level. However, they can be made to hold the induced displacement under activation of a dc voltage, allowing them to be considered for robotic applications. Also, these materials have a faster response, a greater mechanical energy density and they can be operated in air. In contrast, ionic EAP materials (gels, IPMC, conductive polymers, and carbon nanotubes) require drive voltages as low as 1–5 V and produce significant bending. However, bending actuators have relatively limited applications for mechanically demanding tasks due to the low force or torque that can be induced. Also, these materials require maintaining their wetness and when consisting of water at voltages above 1.23-V they suffer electrolysis with irreversible effects. Further, except for conductive polymers it is difficult to sustain dc-induced displacements.

Unfortunately, EAP based actuators that have been developed so far still exhibit low force, which far below their efficiency limits, are not robust, and there are no standard commercial materials available for practical application considerations. Each of the known materials requires adequate attention to the associated unique properties and constraints. In order to be able to take these materials from the development phase to use as effective actuators, there is a need to have an established EAP infrastructure. Effectively addressing the requirements of the EAP infrastructure involves developing adequate understanding of EAP materials' behavior, as well as processing and characterization techniques. Enhancement of the actuation force requires an understanding of the basic principles, computational chemistry models, comprehensive material science, electromechanical analysis and improved material processing techniques. Efforts are made to gain a better understanding of the parameters that control the EAP electro-activation force and deformation. The processes of synthesizing, fabricating, electroding, shaping, and handling are being refined to maximize the EAP materials actuation capability and robustness. Methods of reliably characterizing the response of these materials are being developed to establish databases with documented material properties in order to support design engineers that are considering the use of these materials. Various configurations of EAP actuators and sensors are being modeled to produce an arsenal of effective smart EAP-driven systems. The development of the infrastructure is multidisciplinary and requires international collaboration and these efforts are currently well underway worldwide.

Biomimetic robots

The field of robotics has evolved from automation satisfying the desire to emulate the biological characteristics of manipulation and mobility. In recent years, significant advances have been made in robotics, artificial intelligence and others fields allowing for making sophisticated biologically inspired robots [Bar-Cohen and Breazeal, 2003]. Using these advances, scientists and engineers are increasingly reverse engineering many animals' performance characteristics. Biologically inspired robotics is a subset of the interdisciplinary field of biomimetics.

Technology progress resulted in machines that can recognize facial expressions, understand speech, and perform mobility very similar to living creatures including walking, hopping, and swimming. The emergence of EAP materials has opened a new range of possibilities taking advantage of the remarkably functional characteristic similar to biological muscles.

Making creatures that behave like the biological model is a standard procedure for the animatronics industry that is quite well graphically animates the appearance and behavior of such creatures. However, engineering such biomimetic intelligent creatures as realistic robots is still a challenge due to the need to meet physical and technological constraints. Making simple tasks such as hopping and landing safely without risking damage to the mechanism, or making body and facial expression of joy and excitement, which are very easy tasks for human and animals to do, are extremely complex to engineer. The use of artificial intelligence, effective artificial muscles and other biomimetic technologies are increasingly contributing to the possibility of making realistically looking and behaving robots. At the current biomimetic advancement pace it is becoming more realistic to expect the inevitability of the development of machines as our peers.

This article focuses only on the topic of artificial muscles, their state-of-the-art and the challenges to using them to make fully functional biomimetic intelligent robots. While the engineering challenges are very interesting to address there are also fundamental issues that need attention but they will not be covered herein. Some of these issues include self-defense, rituals for interactions with human, controlled-termination, definition of standard body language for such robots as well as many others. There is already extensive heritage of making robots and toys that look and operate similar to biological creatures and models for such robots are greatly inspired by science fiction (e.g., books, movies, toys, and animatronics). Generally, the current perception and expectations are far beyond the reach of current engineering capabilities that are constrained by laws of physics and current state-of-the-art.

Biology and nature as inspiring models

Evolution over millions of years in nature led to the introduction of highly effective and power efficient biological mechanisms. Imitating these mechanisms offers enormous potentials for the improvement of our life and the tools we use. Humans have always made efforts to imitated nature but the improvement in technology has made it easier to make such adaptation.

The introduction of the wheel has been one of the most important invention that human made allowing to traverse great distances and perform tasks that would have been otherwise impossible within the life time of a single human being. While wheel locomotion mechanisms allow reaching great distances and speeds, wheeled vehicles are subjected to great limitations with regards to traversing complex terrain with obstacles. Obviously, legged creatures can perform numerous functions that are far beyond the capability of an automobile. Producing legged robots is increasingly becoming an objective for robotic developers and considerations of using such robots for space applications are currently underway. Making miniature devices that can fly like a dragonfly; adhere to walls like gecko; adapt the texture, patterns, and shape of the surrounding as the octopus (it can reconfigure its body to pass thru very narrow tubing); process complex 3D images in real time; recycle mobility power for highly efficient operation and locomotion; self-replicate; self-grow using surrounding resources; chemically generate and store energy; and many other capabilities are some of the areas that biology offers a model for science and engineering inspiration. While many aspects of biology are still beyond our understanding and capability, significant progress has been made. Adapting mechanism of nature may be more effective to make by mimicking the functional capability rather than fully copying the mechanisms. The airplane is one such an example where human made attempts over to fly like birds over many centuries have failed as long as human simply tried to copy nature. There is no doubt that human made machines have significantly surpassed biology in flying way higher, faster and perform functions that are far beyond any creature capability.

Biomimetic robots using EAP

Mimicking nature would significantly expand the functionality of robots allowing performance of tasks that are currently impossible. As technology evolves, great number of biologically inspired robots actuated by EAP materials emulating biological creatures is expected to emerge. To promote the development of effective EAP actuators, which could impact future robotics, toys, and animatronics, two platforms were developed (see Figure 3). These platforms are available at the author's lab in JPL and they include an Android head that can make facial expressions and a robotic hand with movable joints. At present, conventional electric motors are producing the required facial expressions of the Android. Once effective EAP materials are chosen, they will be modeled into the control system in terms of surface shape modifications and control instructions for the creation of the desired facial expressions. Further, the robotic hand is equipped with tendons and sensors for the operation of the various joints mimicking human hand. The index finger of this hand is currently being driven by conventional motors in order to establish a baseline and these tendons would be substituted by EAP when such materials are developed as effective actuators.

FIGURE 3: An android head and a robotic hand that are serving as biomimetic platforms for the development of artificial muscles
Acknowledgement: This photo was made at JPL where the head was sculptured and instrumented by David Hanson, University of Texas, Dallas. And the hand was made by Graham Whiteley, Sheffield Hallam U., UK.

The field of artificial muscles offers many important capabilities for the engineering of robots. The easy capability to produce EAP in various shapes and configurations can be exploited using such methods as stereolithography and ink-jet processing techniques. Potentially, a polymer can be dissolved in a volatile solvent and ejected drop-by-drop onto various substrates. Such rapid prototyping processing methods may lead to mass-produced robots in full 3D details including the actuators allowing rapid prototyping and quick transition from concept to full production [Bar-Cohen, 2001]. While such capabilities are expected to significantly change future robots, additional effort is needed to develop robust and effective polymer-based actuators.

Biologically inspired robots

The evolution in capabilities that are inspired by biology has increased to a level where more sophisticated and demanding fields, such as space science, are considering the use of such robots. At JPL, a six-legged robot is currently being developed for consideration in future missions to such planets as Mars. Such robots include the LEMUR (Limbed Excursion Mobile Utility Robot). This type of robot would potentially perform mobility in complex terrains, sample acquisition and analysis, and many other functions that are attributed to legged animals including grasping and object manipulation. This evolution may potentially lead to the use of life-like robots in future NASA missions that involve landing on various planets including Mars. The details of such future missions may be designed as a plot, commonly used in entertainment shows rather than conventional mission plans of a rover moving in a terrain and performing simple autonomous tasks. Equipped with multi-functional tools and multiple cameras, the LEMUR robots are intended to inspect and maintain installations beyond humanity's easy reach in space with the ability to operate in harsh planetary environments that are hazardous to human. This spider looking robot has 6 legs, each of which has interchangeable end-effectors to perform the required mission (see Figure 4). The axis-symmetric layout is a lot like a starfish or octopus, and it has a panning camera system that allows omni-directional movement and manipulation operations.

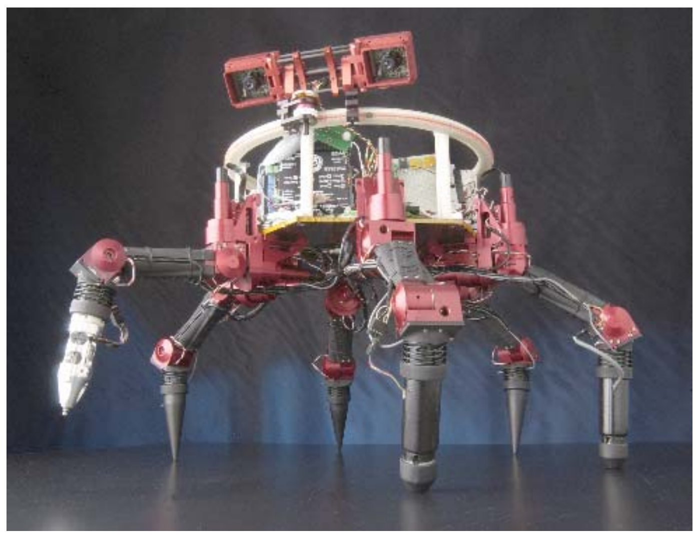

FIGURE 4: A new class of multi-limbed robots called LEMUR (Limbed Excursion Mobile Utility Robot) is under development at JPL [Courtesy of Brett Kennedy, JPL]

Concluding remarks

Technologies that allow developing biologically inspired system are increasingly emerging allowing for the development of robots that can walk, hop, swim, dive, crawl, etc. Making robots that are actuated by artificial muscles and controlled by artificial intelligence would enable engineering reality that used to be considered science fiction. Using effective EAP actuators to mimic nature would immensely expand the functionality of robots that are currently available. Making such robots capable to understand and express voice and body language would increase the probability of seeing them as social partner than a machine or tool. As the technology advances are made, it is more realistic to expect that biomimetic robots will become commonplace in our future environment. It will be increasingly difficult to distinguish them from organic creatures, unless intentionally designed to be fanciful. As we are inspired by biology to improve our lives we will increasingly be faced with challenges to such implementations. A key to the development of such robots is the use of actuators that mimic muscles, where electroactive polymers (EAP) have emerged with this potential. A series of new artificial muscle materials were developed while the technology infrastructure is being established towards making more efficient material and design effective mechanism. The author's arm-wrestling challenge having a match between EAP-actuated robots and a human opponent highlights the potential of this technology. This match may occur in the coming years and success of a robot against human opponent will lead to a new era in both making realistic biomimetic robots and implementing engineering designs that are currently considered science fiction.

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